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Investigation on Machining Performance of Amplitude Control Sculpturing Method in Elliptical Vibration Cutting

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Abstract

The authors have proposed a unique micro/nano sculpturing technology for difficult-to-cut materials by controlling vibration amplitude in elliptical vibration cutting. In the present research, machining performance of the amplitude control sculpturing method is investigated, and limitation in nano-scale machining is explored. In the proposed machining method, the machinable part geometry is essentially restricted by cutting tool geometry and vibration conditions. In order to clarify the machining performance of the proposed technology, a series of analytical and experimental investigations were conducted. From the experimental results, it was confirmed that nano structures with a step height of more than 2 nm and a pitch of more than 250 nm can be machined with surprisingly high accuracy of about 1 nm. On the other hand, a considerable error between the amplitude command and the envelope of tool trajectory is generated when the slope of the machining part geometry becomes large. In order to overcome this error, a compensation method of the amplitude command is proposed. By applying the proposed compensation, nano structures with large ratio of the step height to the pitch were machined accurately. The proposed machining method was subsequently applied to a three-dimensional grid surface machining, and successful experimental results verified feasibility of practical machining application by applying proposed technology.

Keywords: Elliptical vibration cutting, nano machining, hardened steel, amplitude control sculpturing method;

1. Introduction

Textured surfaces with sophisticated micro-nano structures can provide interesting functions, such as hydrophobicity, low friction, optical functions, and so on. In order to put those unique functions into practical use, high performance manufacturing technology is required to attain mass production of products with the textured surfaces. Fast tool servo (FTS) technology has been utilized to fabricate micro-nano structures in a variety of applications [1, 2]. While efficient micro-nano scale texturing can be achieved by the FTS technology with single crystal diamond tools, it is impossible to apply this method to machining of steel materials because of rapid tool wear and surface deterioration. Steel is a typical material which is used for mechanical elements or their molding, but the single crystal diamond tools are essentially not applicable to the steel machining due to strong chemical affinity.

On the other hand, elliptical vibration cutting technology [3] is one of potential methods to attain efficient textured surface machining of steel materials. By applying ultrasonic elliptical vibration during machining, thermo-chemical reactions between diamond and steel can be suppressed significantly, resulting in successful ultraprecision machining with no serious tool wear [4]. It has been clarified that ultraprecision machining of not only steel materials but also hard brittle materials, such as glass, sintered tungsten carbide, and tungsten alloy [5,6,7], can be attained by the single crystal diamond tools.

Furthermore, the authors have proposed a unique micro-nano sculpturing method by using the elliptical vibration cutting technology [8]. In the proposed method, the vibration amplitude of the elliptical vibration is

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controlled during machining. Because of this amplitude control, depth of cut can be changed quickly as the conventional FTS does. In the past study, fundamental sculpturing experiments were performed and simple micro-nano textured machining was successfully attained [8]. While fundamental idea has been verified, its machining performance is not studied well. In order to investigate feasibility of practical applications by the proposed technology, the limitation in machinable part geometry and machining accuracy need to be clarified.

In this paper, a series of experimental investigations are carried out. First, the machining accuracy in nano-scale machining is explored experimentally. Relationship between amplitude command and machined shape is also analyzed. Then, compensation method of the amplitude command is proposed to increase machining accuracy. The proposed method is, subsequently, applied to surface texturing application of angle grid. Through a series of experiments and analyses, the machining performance of the amplitude control sculpturing method is evaluated.

2. Principle of amplitude control sculpturing method

In the elliptical vibration cutting, the tool is fed at a nominal cutting speed and vibrated elliptically at the same time. The nominal cutting speed is set to be lower than the maximum vibration speed to ensure that the tool can be separated from the workpiece in each vibration cycle. Because of this intermittent process, significant decrease in the chip thickness as well as the cutting forces can be attained [3, 9]. Moreover, the separation in each vibration cycle is also advantageous to prevent the adhesion of the workpiece to the diamond tool and the thermo-chemical wear. And thus, the ultra-precision cutting of hardened steel can be achieved with the single crystal diamond tools.

Fig. 1 demonstrates the amplitude control sculpturing method, where vibration amplitude in a depth of cut direction is sinusoidally controlled in the elliptical vibration cutting. The trajectory of the cutting edge, then, changes dynamically, and its envelope is transferred to the finished surface. By controlling the amplitude ultra-precisely at high speed, the ultraprecision sculpturing of the difficult-to-cut materials can be achieved efficiently without using conventional FTS technology. In other words, the elliptical vibration cutting technology is already equipped with a FTS function by itself [8].

On the other hand, there are several restrictions in machinable part geometry due to the specific process. For instance, steep down slope cannot be machined due to interference of tool flank face to workpiece. Machinable part geometry depends on a clearance angle of a tool. In addition, amplitude command wave does not fully correspond to the envelope of the cutting edge trajectory, as shown in Fig. 1. If the cutting slope is steep, then amplitude command shape needs to be compensated according to target machining shape.

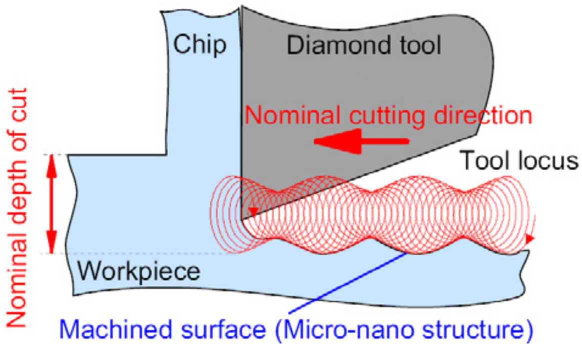


Fig. 1. Amplitude control sculpturing in elliptical vibration cutting

3. Experimental setup for micro-nano sculpturing of textured surfaces

A two-degree-of-freedom (2-DOF) elliptical vibrator, EL-50Σ made by Taga Electric Co., Ltd., is utilized in the present study. It is actuated by using PZT actuators. As the vibrator is designed to have the same resonant frequencies in the second resonant mode of longitudinal vibration and the fifth resonant mode of bending vibration, it can generate large longitudinal and bending vibrations simultaneously at the same ultrasonic frequency of about 36.2 kHz. Thus, a 2-DOF elliptical vibration can be obtained at the diamond tool tip attached to the vibrator, as shown in Fig. 2 [8]. The vibration amplitude can be controlled arbitrary within a bandwidth of about 300 Hz by external command voltage.

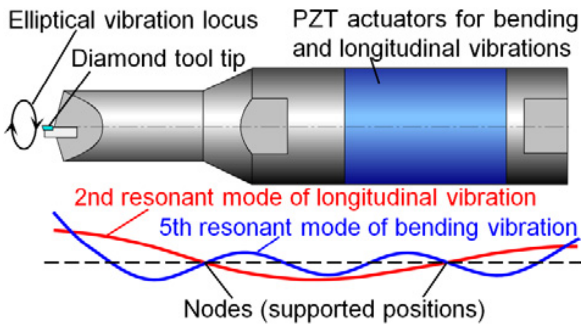


Fig. 2. 2-DOF elliptical vibrator

The proposed amplitude control sculpturing method is applied to textured surface machining, where the vibration amplitude is controlled in synchronization with planing motion of an ultraprecision machine tool. Fig. 3 shows an experimental setup. The ultraprecision machine tool, ASP01UPX made by Nachi-Fujikoshi Corp., is used. The 2-DOF elliptical vibrator was attached to X axis table. The vibration amplitude in the depth of cut direction along Z-axis is controlled in synchronization with the cutting feed motion in X-axis. X feed position is detected by using an external optical sensor in each stroke, and a high-speed real-time control system outputs vibration amplitude command in a synchronization with the X axis feed.

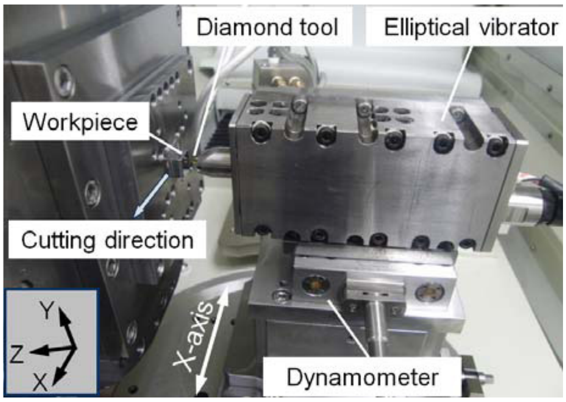


Fig. 3. Experimental setup

4. Ultraprecision nano sculpturing of textured surfaces

4.1. Machining accuracy in trapezoidal structure machining

In order to investigate machining accuracy on hardened steel (JIS: SUS420J2, UTS≥540 MPa, HRC53), nano structures were machined with trapezoidal amplitude command waves at 100 Hz. A step height of trapezoidal command was controlled to change a depth of cut from 1 nm to 20 nm, and a pitch of the trapezoidal structures was set to be 7 μm. The machine tool is simply controlled to machine a plane surface in XY plane with a pick feed of 5 μm at a constant feed speed of 42 mm/min. The vibration amplitude in the depth of cut direction along Z axis is controlled in synchronization with the cutting feed in X axis. Then, the trapezoidal structures perpendicular to X axis were machined. Fig. 4 shows the experimental results. The machining surface was measured by using Atomic Force Microscope (AFM). As shown in Fig. 4, nano structures with a step height of at least more than 2 nm are distinctive from the machined hardened steel surface.

Machining accuracy of trapezoidal steps was investigated from the measured geometry. In order to distinguish machining error due to the machine tool motion control, average machining height was analyzed. Note that the motion error of the machine tool is not negligible in single-nano scale. Fig. 5 shows relationships between step height commands and measured step heights. The error bar indicates standard deviation ($\pm 1\sigma$) of the measured heights, which represents height variation. From Fig. 5, the measured machining error is almost within 1 nm at the step height command of larger than or equal to 3 nm. But the measured step height becomes smaller than the command at the step height command of less than 3 nm. From the measured results, the nano structure with a step height of more than 2 nm can be machined within a machining accuracy of about ±1 nm.

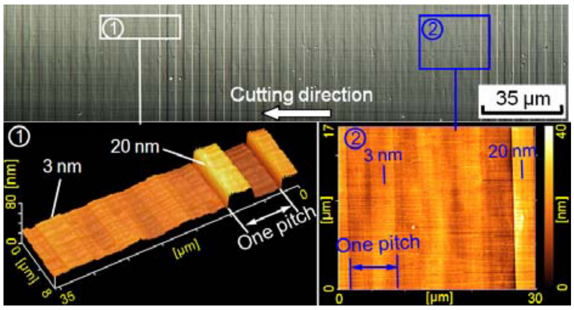


Fig. 4. Optical microphotograph and AFM images of machined trapezoidal structures

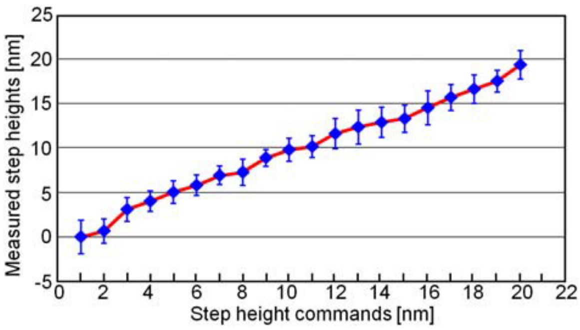
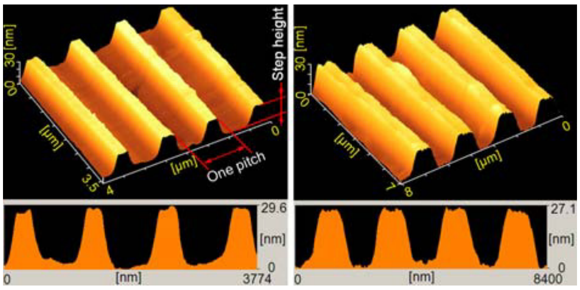


Fig. 5. Measured step heights

4.2. Nano structure machining on hardened steel

Several nano patterns were machined with a steady amplitude commands at 100 Hz. In order to avoid the flank contact to the workpiece surface, the summation of the slope of amplitude change and the critical entrance angle θ_1 [3] in elliptical vibration cutting plane surface needs to be less than the clearance angle of the cutting edge at least. As the tool with a clearance angle of 40 deg was utilized here, the slope of the trapezoidal structure was kept to 30 deg. Fig. 6 shows trapezoidal structures machined by the amplitude corresponding to 25 nm step height with pitches of 2 μm and 1 μm, respectively. The nano textured surfaces were machined successfully on hardened steel. The measured machining step heights and pitches agreed with designed values accurately.



(a) 1µm pitch (b) 2µm pitch

Fig. 6. Machined trapezoidal structures with 25 nm height

Fig. 7 shows machined structures with different patterns, i.e., sinusoidal, zigzag and ramp waves. Nano patterns with a step height of 10 nm and a pitch of 500 nm were machined successfully. It should be note that measured AFM data of the sinusoidal nano structure was processed through a low pass filter with a wavelength of 200 nm to remove spike noises.

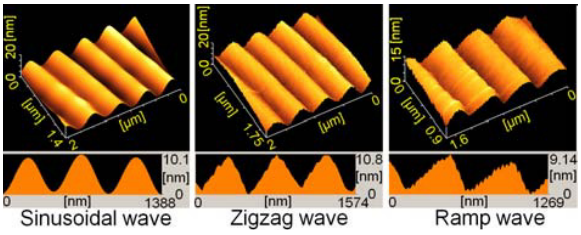


Fig. 7. Nano structures with step height of 10 nm and pitch of 500 nm

4.3. Compensation amplitude control command

When the ratio of the step height to wavelength is large, i.e., steep structure machining, the machined part geometry does not precisely correspond to the controlling amplitude command. Fig. 8 shows simulated cutting edge trajectory, where the step height and the pitch of the amplitude command are set to be 100 nm and 1 µm, i.e., the ratio is 0.1. From Fig. 8, a not negligible error between the amplitude command and the machined geometry can be observed. As the tool vibrates not only in the depth of cut direction but also in the cutting direction, the envelope of the cutting edge trajectory becomes shallow with respect to the command wave. This over cut causes serious machining accuracy deterioration especially when the ratio of step height to wavelength is large.

In order to cancel out this machining error, the amplitude commands in the cutting direction and the depth of cut direction were modified simultaneously. Fig. 9 shows a schematic illustration of the command compensation method. The tool path with the elliptical vibrations (x_e, u_e) can be formulated by vibration amplitudes (A_c, A_d) in the cutting and the depth of cut directions, the vibration frequency ω, the phase shift φ and the nominal cutting speed v_c as following:

$$x_e = A_c \sin \omega t + v_c t, \quad u_e = A_d \sin(\omega t + \varphi) \tag{1}$$

By comparing to the target shape (x_t, u_t), numerical computation gives the maximum over cut value in nth vibration cycle representing the machining error e_n.

$$e_n(x_n) = u_t(x_n) - u_e(x_n) \tag{2}$$

Then, the amplitude command, which agrees with target shape initially, is compensated by taking subtract e_n from the initial amplitude command. By applying this compensation to each vibration cycle, theoretical machining error is roughly cancelled out.

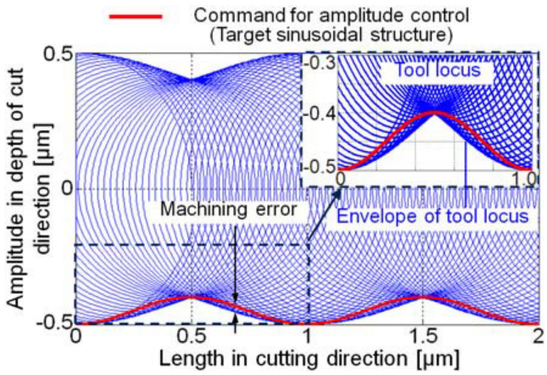


Fig. 8. Cutting edge trajectory with a large ratio of step height to wave length

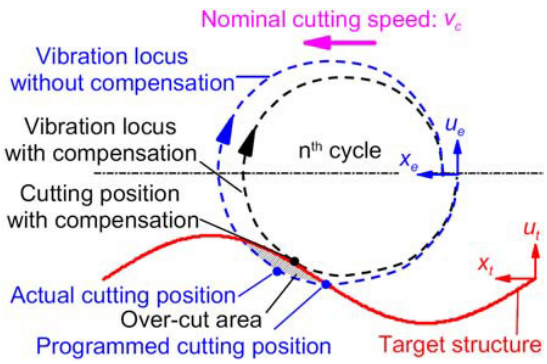


Fig. 9. Proposed amplitude command compensation method

Fig. 10 demonstrates a compensated vibration locus to machine a sinusoidal wave with a step height of 100 nm and a pitch of 1 µm. The envelop profile of the tool trajectory is accurately identical with the ideal target profile by applying the proposed command compensation method. Consequently, the machining error can be decreased significantly.

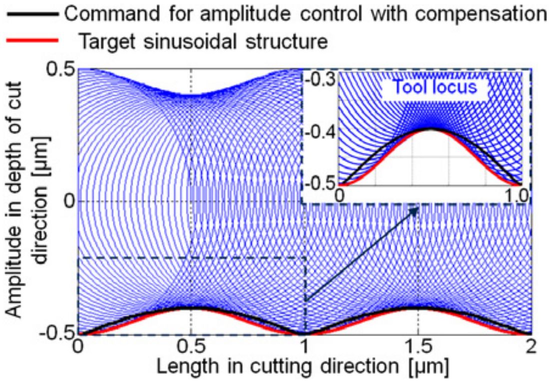


Fig. 10. Computational result with command compensation

Fig. 11 (a) shows the machining result without the command compensation. Due to the over cut error, sinusoidal wave is deteriorated into the serrated wave as shown in Fig. 8. On the other hand, Fig. 11 (b) shows sinusoidal structure machined by the proposed command compensation method. The machining error is decreased significantly. Through the experimental verifications, it was confirmed that the proposed command compensation method is useful to improve the machining accuracy deterioration due to the over cut error.

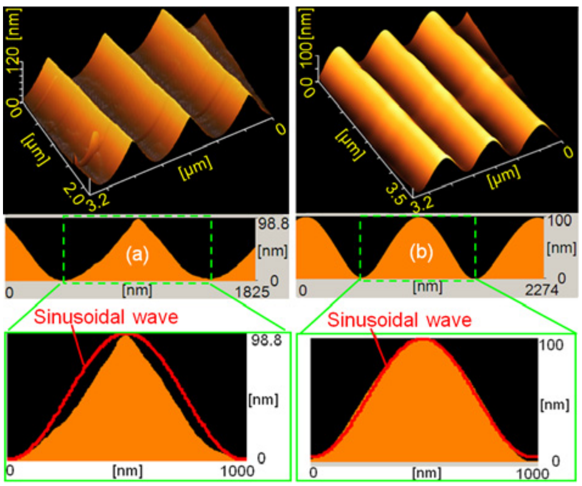


Fig. 11. Sinusoidal structure with height of 100 nm and pitch of 1 μm (a) without/ (b) with command compensation

Fig. 12 shows a sinusoidal nano structure with the measured height of 3.5 nm and the wavelength of 250 nm, which was machined with the amplitude command compensated by the proposed method. The measured AFM data was processed through a low pass filter with a wavelength of 100 nm to remove spike noises. Surprisingly, the smooth nano structure can be machined accurately.

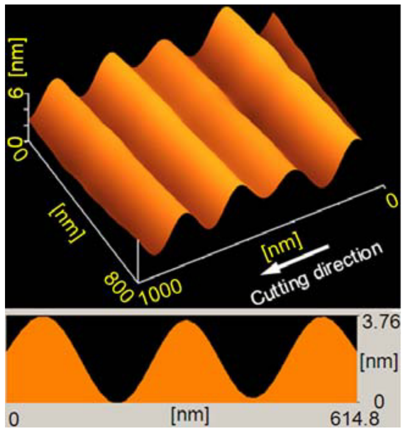


Fig. 12. Nano sinusoidal structure with the height of 3.5 nm and wavelength of 250 nm

5. Application of sinusoidal grid surface fabrication

In order to investigate the feasibility of the practical application, the proposed machining method was applied to a three-dimensional micro/nano structure sculpturing. Fig. 13 shows target machining geometry, i.e., an angle grid surface [10].

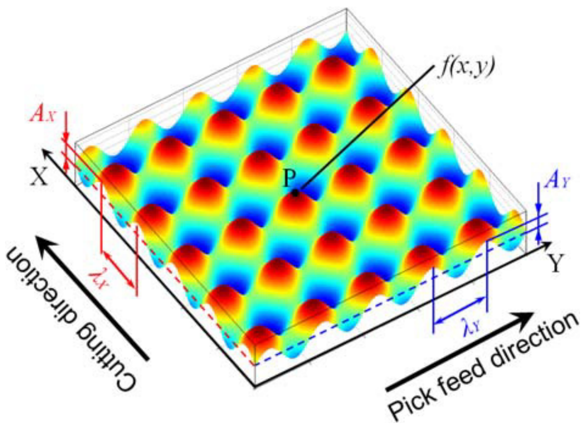


Fig. 13. Schematic of the angle grid

The height of arbitrary point P can be given by Eq. (3) [10, 11];

$$f(x,y) = A_X \sin(\frac{2\pi}{\lambda_X}x) + A_Y \sin(\frac{2\pi}{\lambda_Y}y) \tag{3}$$

where A_X and A_Y are amplitudes of the sine functions in the X direction and the Y direction, respectively. λ_X and λ_Y are the corresponding wavelengths. Here target amplitude is set to be 0.5 μm. From the restrictions due to the tool geometry, i.e., a nose radius of 1.04 mm, the wavelength was set to be λ_X=λ_Y=150 μm. The sinusoidal structure is machined by the amplitude control sculpturing method with a sinusoidal amplitude command at 100 Hz in the cutting direction. The cutting speed is set to be 900 mm/min. As the ratio of the machining height to the pitch is small, the amplitude command is not compensated here. On the other hand, the height position along the pick feed direction was controlled by utilizing positioning of the ultraprecision machine tool. A pick feed is set to be 3 μm.

Fig. 14 shows a microphotograph and a profile of the machined angle grid surface measured by optical microscope. It was confirmed that the periodic nano structure with smooth surface is obtained on the hardened steel workpiece. The machined height (1.005 μm) and the wavelength (150 μm) along the cutting direction and the pick feed direction correspond accurately to the theoretical values.

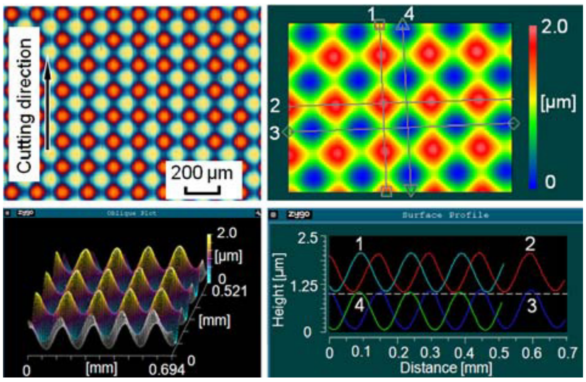


Fig. 14. Machined angle grid surface with height of 1 μm and wavelength of 150 μm

6. Conclusion

Machining performance of amplitude control sculpturing technology for difficult-to-cut materials at micro/nano scale was investigated by utilizing elliptical vibration cutting. A series of micro/nano sculpturing experiments on hardened steel were carried out, and machining accuracy was investigated by applying amplitude control commands with simple trapezoidal, sinusoidal, zigzag, and ramp waves. Furthermore, a compensation method of a machining error caused by disagreement of the amplitude command shape and envelop of the cutting edge trajectory is proposed. Through an experimental verification, it was confirmed that the proposed compensation improves the machining accuracy significantly. Consequently, a sinusoidal structure with a large ratio of step height (100 nm) to wavelength (1 μm) was machined successfully. Based on the machining performance investigation, the machining experiment of a sophisticated three-dimension micro/nano structure, i.e., an angle grid surface, was carried out on the hardened steel workpiece. The experimental result verified feasibility of efficient micro/nano machining by the proposed method.

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